Importance of Coherent Beam-Beam Effects to the Compensation of Beam-Beam Tune Spread in Hadron Collider

Lihui Jin, Jack Shi

University of Kansas

Features of the Code

- Self-consistent beam-beam kicks in transverse space are calculated with PIC method.
  - Size of adaptive grid is matched with beam.
  - Large number of macro-particles is necessary for hadron beams in nonlinear regime of beam-beam interactions.

- Computing
  - dynamics of beam tune spread
  - dynamics of beam particle distributions

Formulas and method

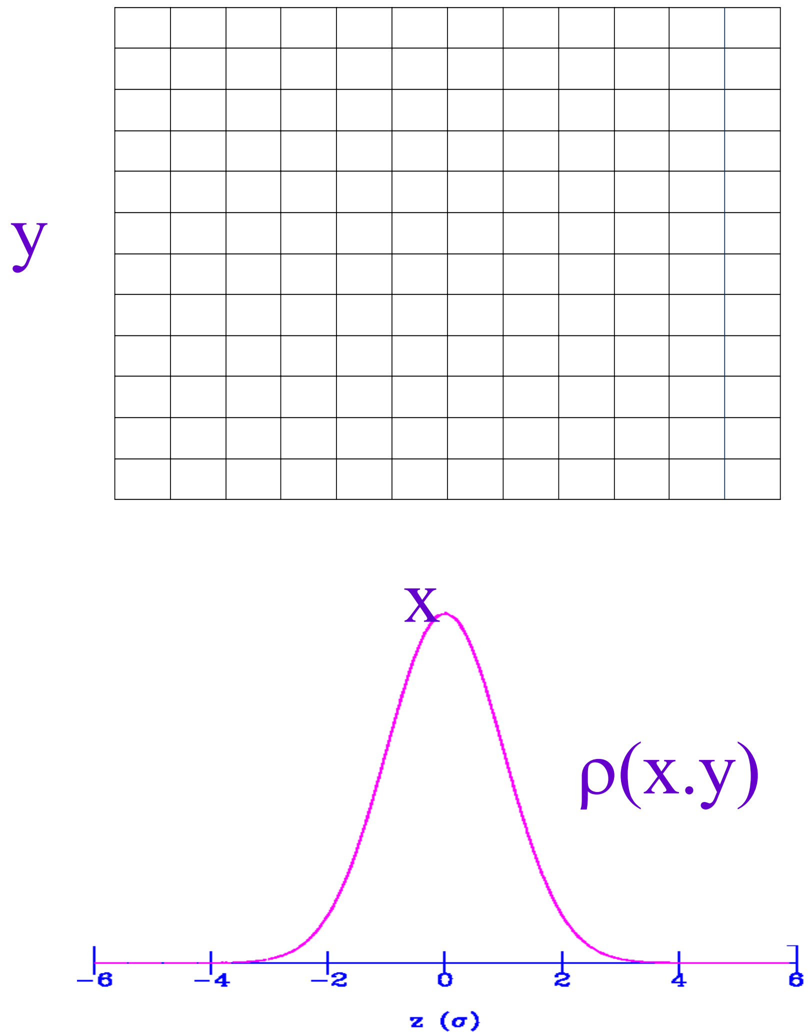
- Kick at IPs:

$$\Delta\vec{r}\,' = \int d\vec{\tilde{r}}\,\rho(\vec{\tilde{r}})\vec{G}(\vec{r}-\vec{\tilde{r}}) \qquad \vec{r} = (x, y)$$

$$\vec{G}(\vec{r}-\vec{\tilde{r}}) = G_0 \frac{(\vec{r}-\vec{\tilde{r}})}{(\vec{r}-\vec{\tilde{r}})^2}$$

$$G_0 = 2Nr/\gamma = \begin{cases} 4\pi\xi_x\sigma_x^*(\sigma_x^*+\sigma_y^*)/\beta_x^* \\ 4\pi\xi_y\sigma_y^*(\sigma_x^*+\sigma_y^*)/\beta_y^* \end{cases}$$

PIC Calculation of Beam-Beam Kick



The x-y space covered by an uniform mesh

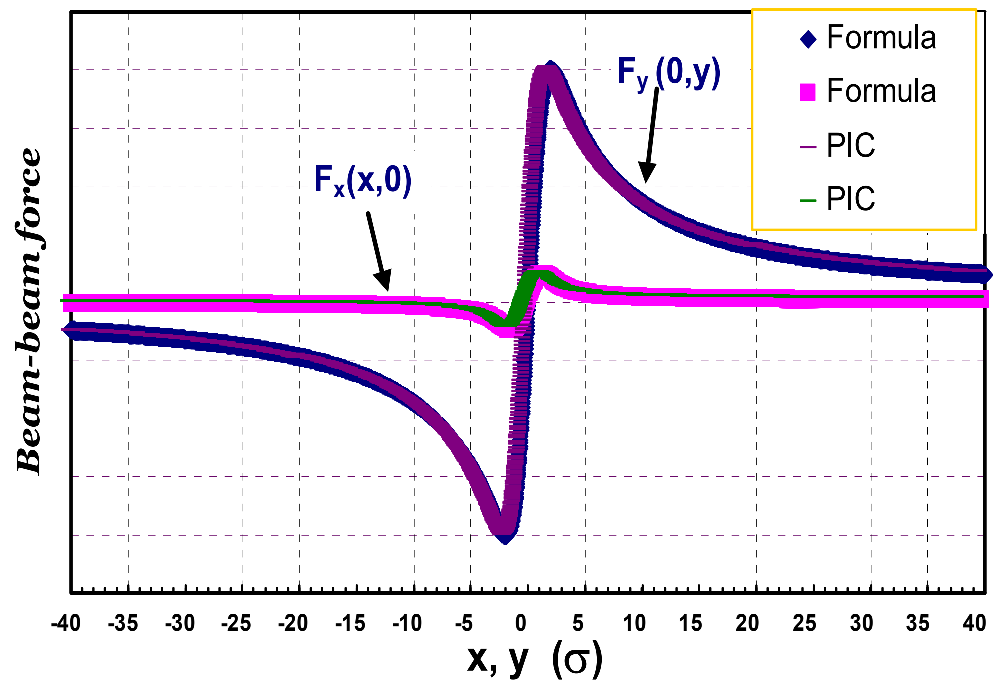
ρ(x,y) obtained by 4-point-cloud in cell

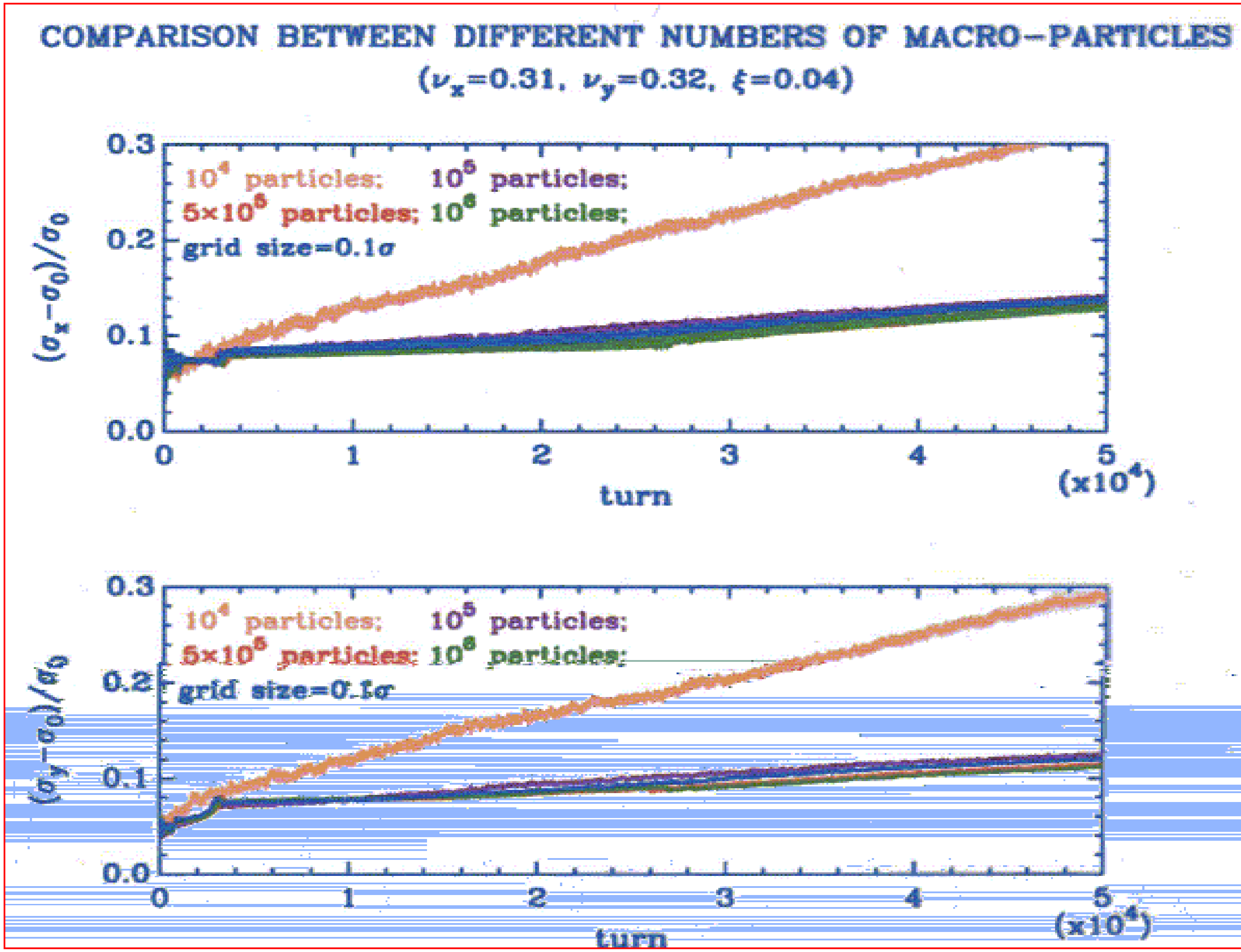
The forces calculated at the grid points

The fields interpolated to the position of every particle

Convergence of the Code

- number of macro-particles
- size of mesh
- grid constant

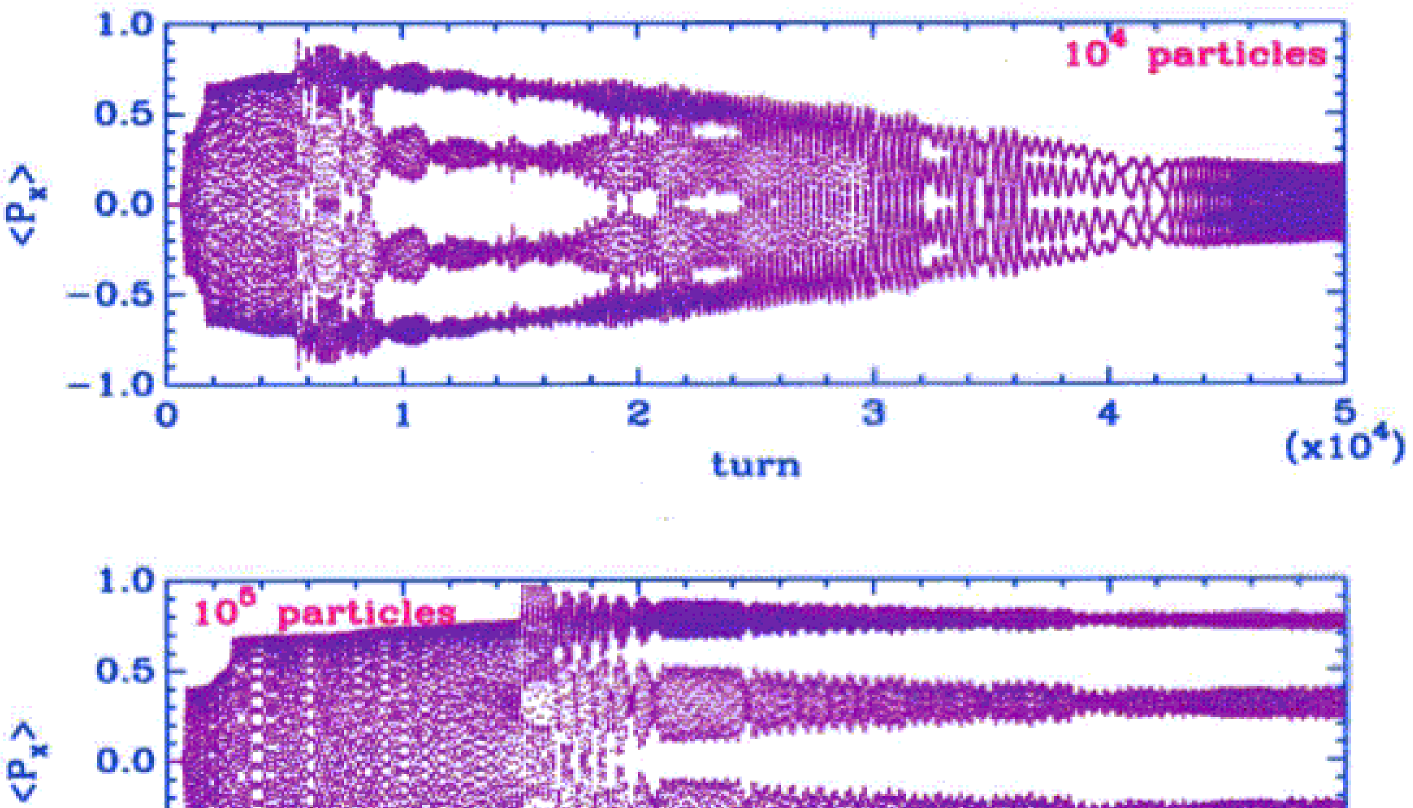




Fewer than 10^5 macro-particles are not enough to reveal true beam dynamics in nonlinear regime of beam-beam interactions.

COMPARISON BETWEEN DIFFERENT NUMBERS OF MACRO–PARTICLES

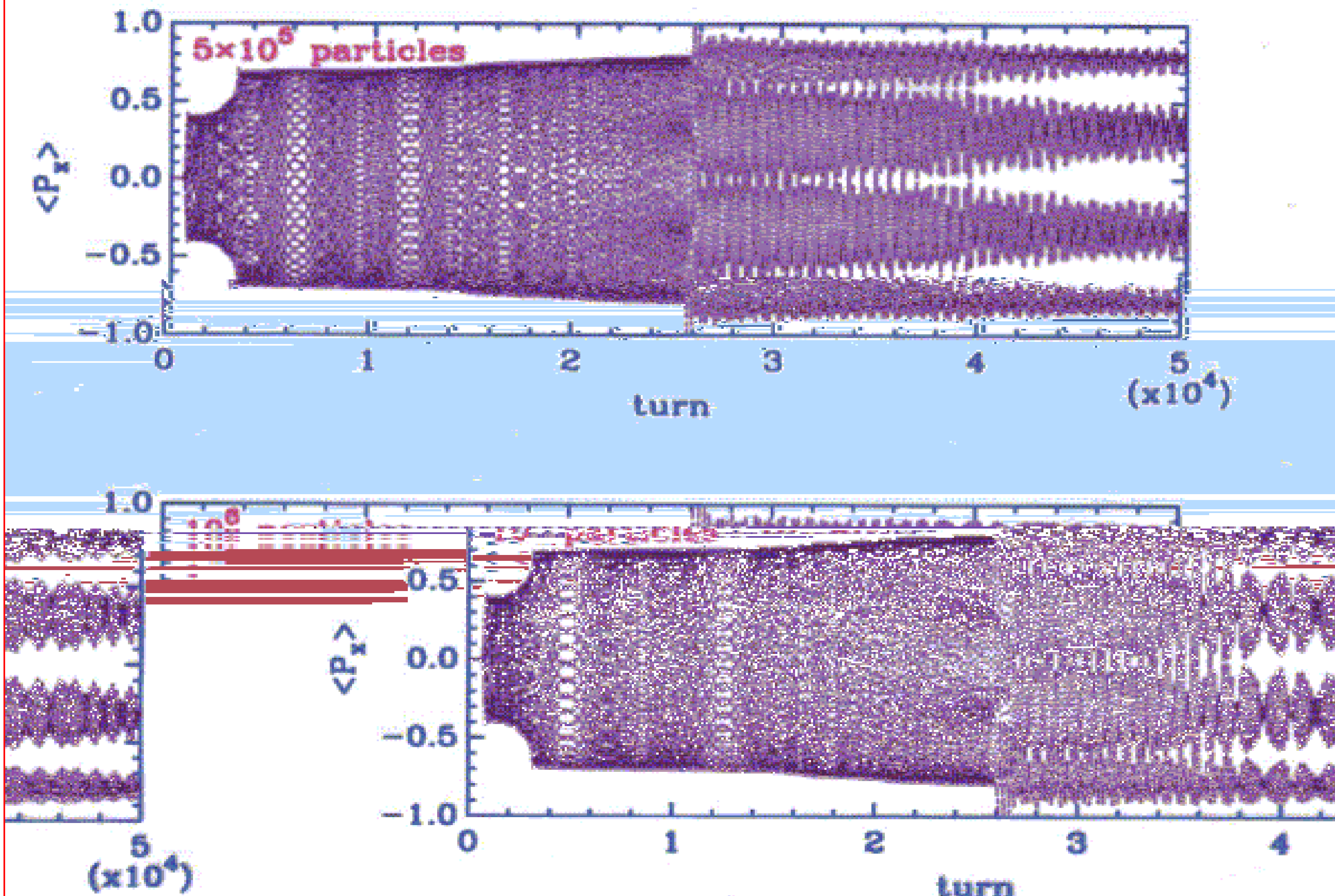
$(\nu_x=0.31,\ \nu_y=0.32,\ \xi=0.04)$

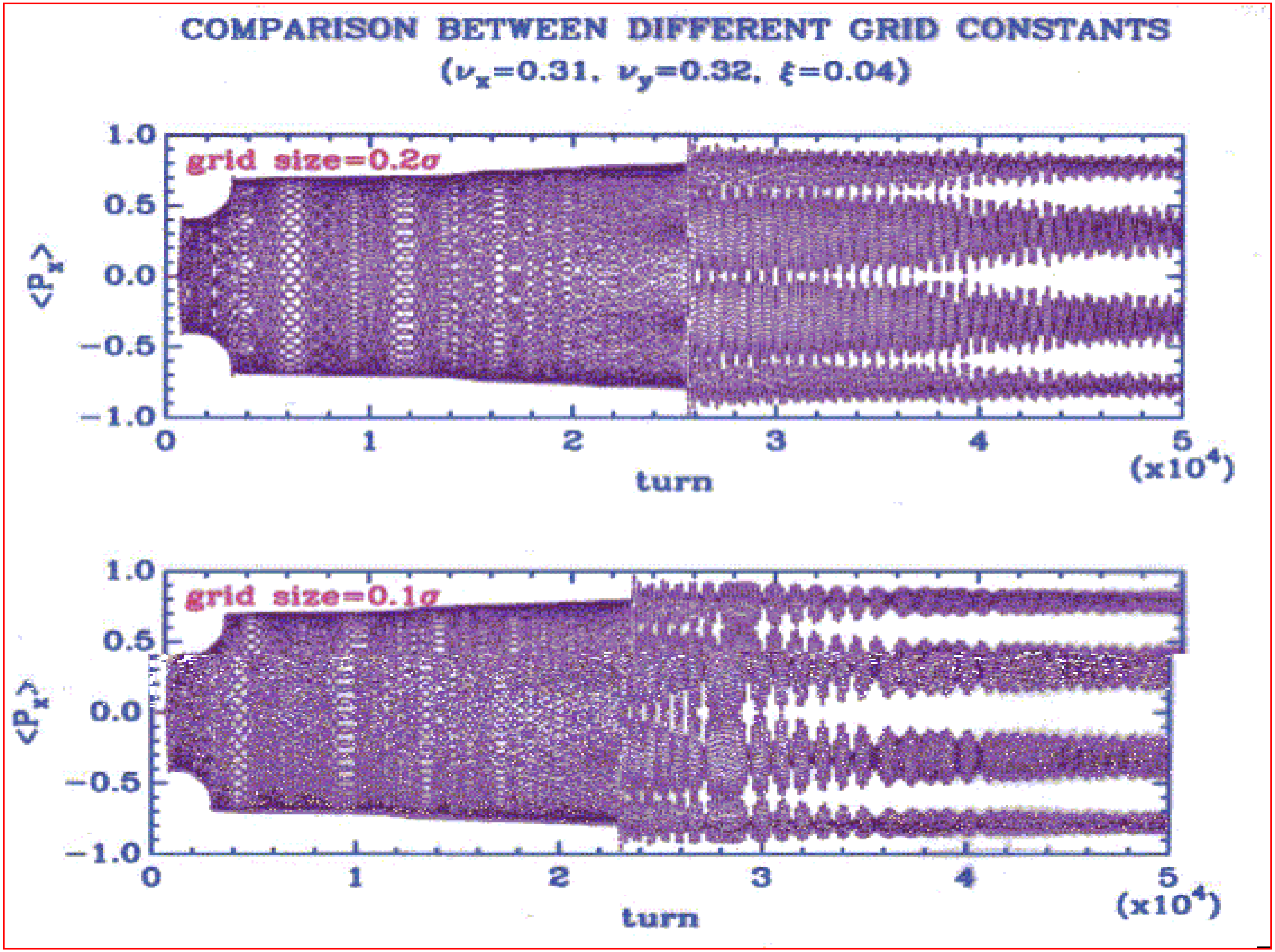


[redacted]

COMPARISON BETWEEN DIFFERENT NUMBERS OF MACRO-PARTICLES

(ν_x=0.31, ν_y=0.32, ξ=0.04)




COMPARISON BETWEEN DIFFERENT GRID CONSTANTS
(ν_x=0.31, ν_y=0.32, ξ=0.04)
grid size=0.2σ
⟨P_x⟩
1.0
0.5
0.0
−0.5
−1.0
0
1
2
3
4
5
($\times 10^4$)
turn
grid size=0.1σ
⟨P_x⟩
1.0
0.5
0.0
−0.5
−1.0
0
1
2
3
4
5
($\times 10^4$)
turn

INTRODUCTION

- A large beam-beam tune spread may lead to crossings of many high-order resonances. The compensation of the beam-beam tune spread has therefore been explored for a reduction of nonlinear beam-beam effects in hadron colliders.

- In this work, the importance of beam-beam tune spread to the chaotic coherent beam-beam instability was studied. It showed that in the nonlinear regime of beam-beam interactions, a beam-beam tune spread of a certain size is usually necessary to the stability of hadron beams.

- Recent beam experiments on HERA confirmed this conclusion.

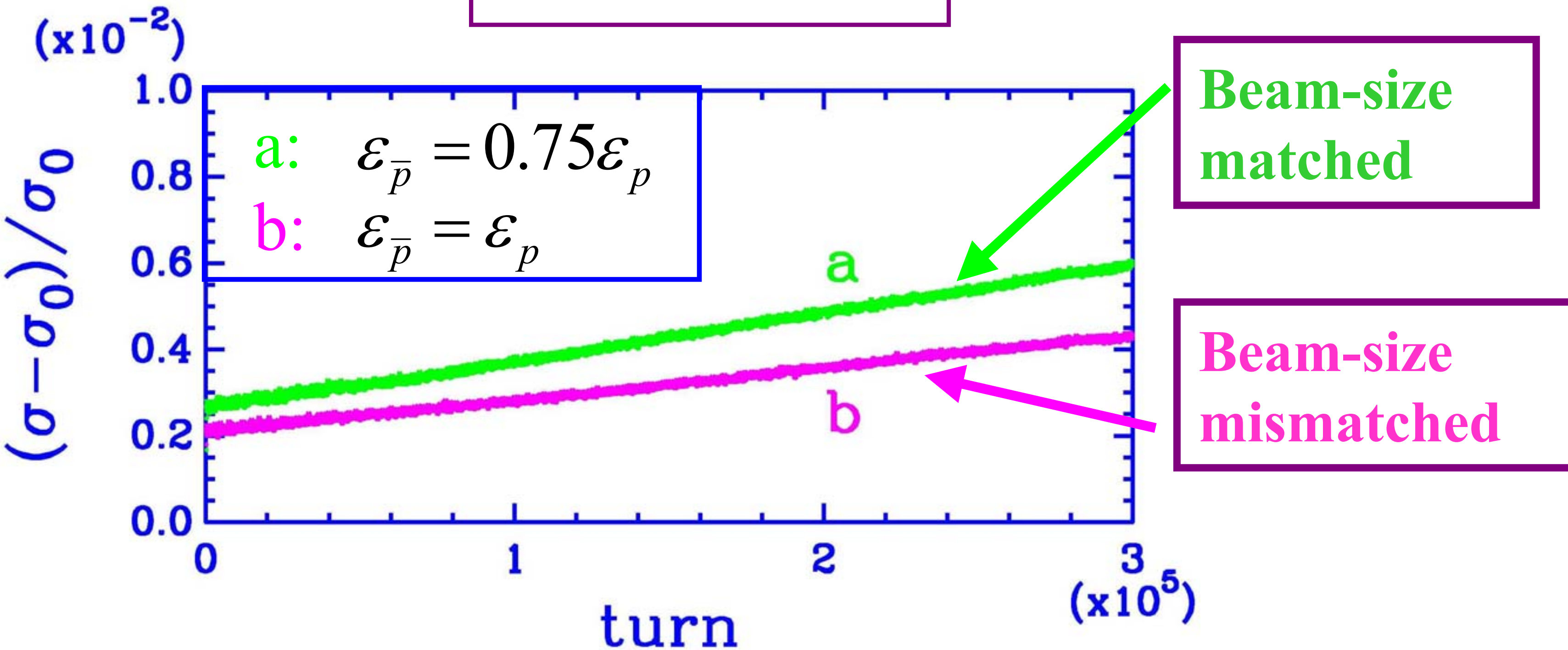
- The study was conducted with a self-consistent beam-beam simulation with PIC method in model lattices of Tevatron and LHC.

Evolution of r.m.s. Beam-Size of the Antiproton Beam

TEVATRON MODEL

$(\nu_x, \nu_y) = (0.582\ , 0.574\ )$

$\xi_{\bar{p}p} = -0.01, \xi_{p\bar{p}} = -0.002$



⇩

The beam-size growth rate in the mismatched collisions is larger than that in the matched case.

"Bad" and "Good" of Beam-Beam Tune Spread

$$H = \nu \square I + H_{\text{beam-beam}}(I, \phi, t)$$

$$= \nu \square I + \underbrace{< H_{\text{beam-beam}} >}_{} + \underbrace{\{H_{\text{beam-beam}}\}}_{}$$

Average part — integrable — "linear"

Oscillating part — nonintegrable — "nonlinear"

In near-linear regime, $< H_{\text{beam-beam}} >$ dominates beam-beam interactions.

In nonlinear regime, $\{H_{\text{beam-beam}}\}$ is important.

Bad :

□ A large tune spread could result in crossings of bad resonance in case of a "bad" working point.

Good:

□ In nonlinear regime, a larger tune spread could result in a stronger Landau damping that could suppress chaotic coherent beam-beam instability.

□ Existence of a large tune spread reduces the possibility of trapping particles inside a resonance.

Comment:

For high-intensity hadron beams, beam-beam interaction is likely to be in the nonlinear regime and the beam-beam tune spread does more good than bad to the beam stability, except in the case of bad working point.

Compensation of Beam-Beam Tune Spread with Electron Beams

$$H = \vec{\nu}\cdot\vec{I} + H_{\bar{p}p}(I,\phi,t) + H_{\bar{p}e}(I,\phi,t)$$
$$= \vec{\nu}\cdot\vec{I} + (<H_{\bar{p}p}> + <H_{\bar{p}e}>)$$
$$+ (\{H_{\bar{p}p}\} + \{H_{\bar{p}e}\})$$

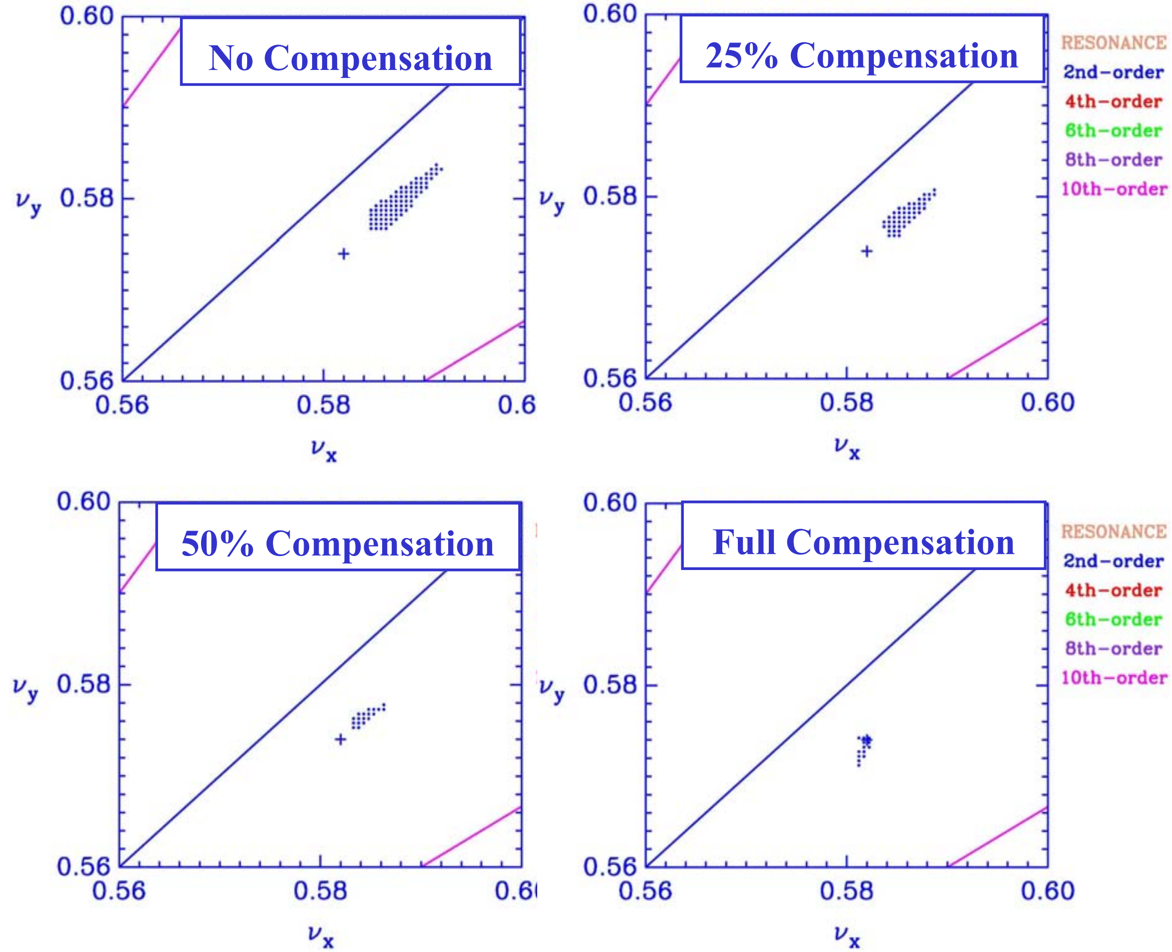
e-beam compensation:

Reduce $(<H_{\bar{p}p}> + <H_{\bar{p}e}>)$

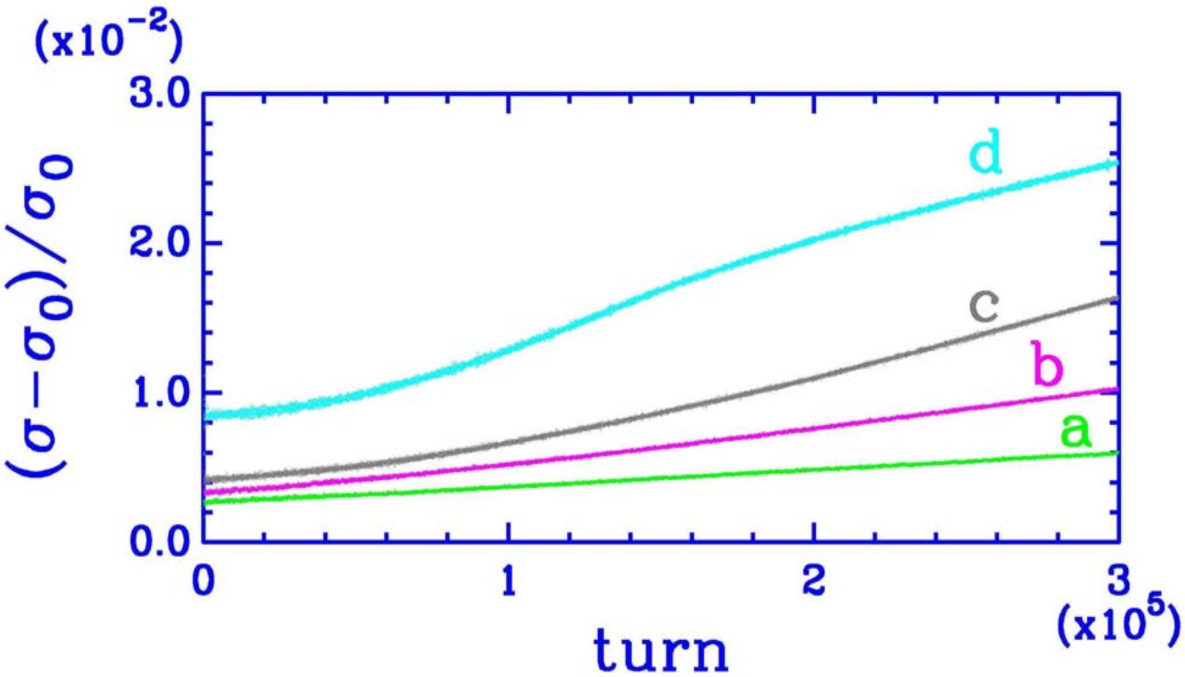
TEVATRON MODEL

$$(\nu_x, \nu_y) = (0.582, 0.574)$$
$$\xi_{\bar{p}p} = -0.01, \xi_{p\bar{p}} = -0.002$$

Tune Spread of the antiproton beam with or without the Compensation



Evolution of r.m.s. Beam-size of the Antiproton Beam



TEVATRON MODEL

$$(\nu_x, \nu_y) = (0.582, 0.574)$$
$$\xi_{\bar{p}p} = -0.01, \xi_{p\bar{p}} = -0.002$$

a : No compensation

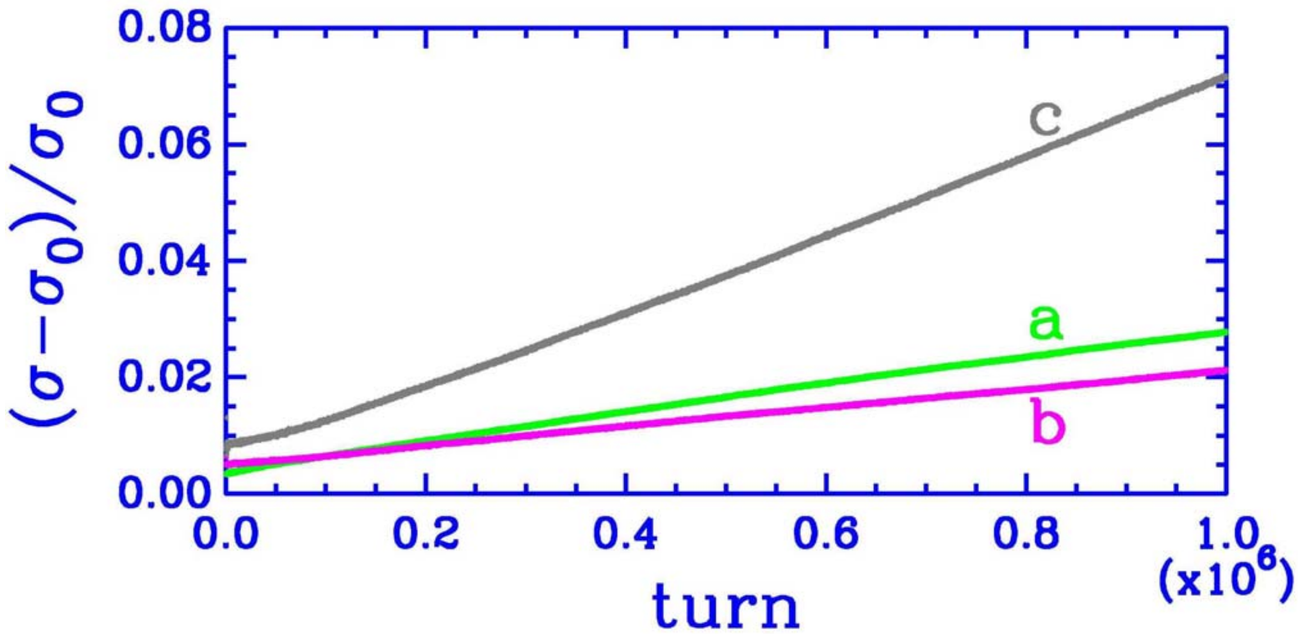
b : 25% compensation

c : 50% compensation

d : Full compensation

At the nominal working point, the compensation of beam-beam tune spread with electron beams could damage the beam stability .

Evolution of r.m.s. Beam-size of the Antiproton Beam When Two Beams Have Different Tunes



TEVATRON MODEL

$\bar{p}: \quad (\nu_x, \nu_y) = (0.582, 0.574)$

$p: \quad (\nu_x, \nu_y) = (0.587, 0.579)$

a : No compensation

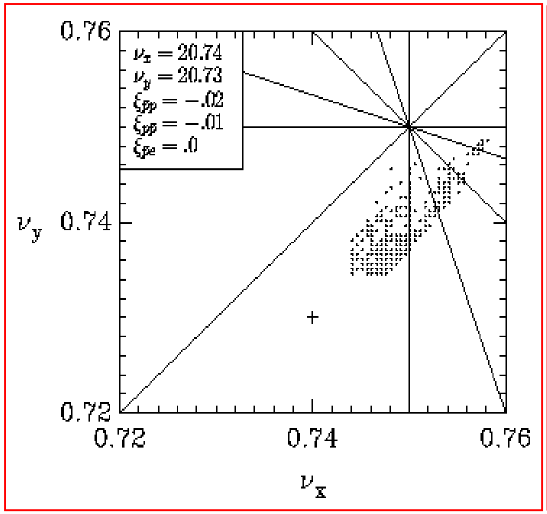
b : 50% compensation

c : Full compensation

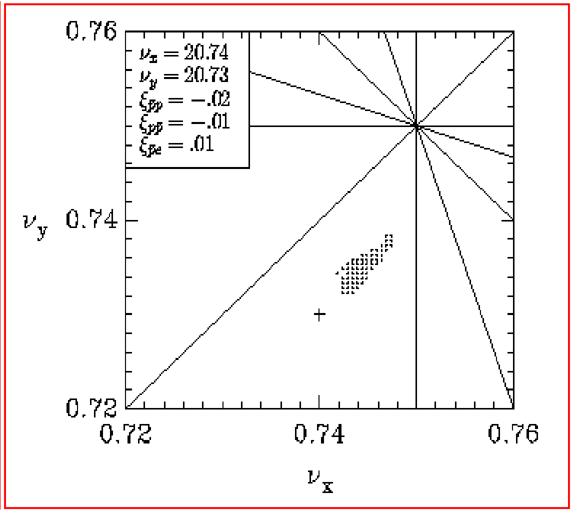
- **When the tune split is big enough (0.005), the tune-spread compensation up to a certain degree could benefit the pbar beam.**
- **The fact that the tune of the p beam has an impact on the dynamics of the pbar beam confirms the existence of collective beam-beam effects in a strong-weak situation of beam-beam interactions.**

Tunes Close to the 4th-Order Resonance

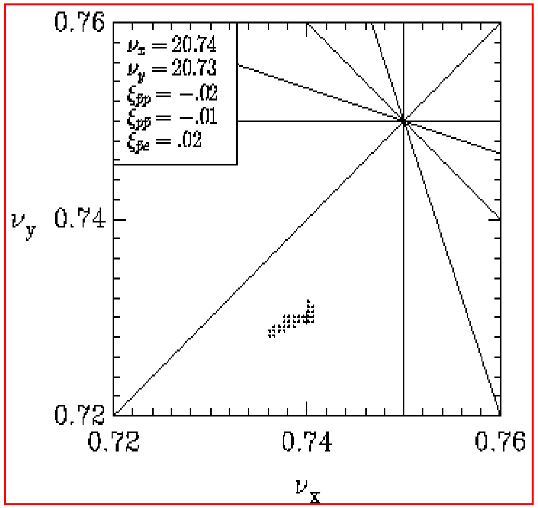
Beam-Beam Tune Spread of the Antiproton Beam



No compensation



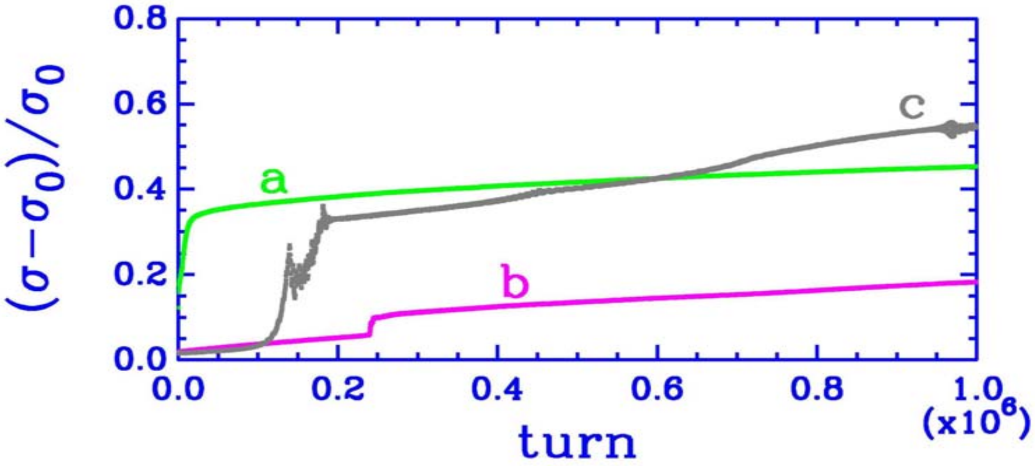
Half compensation



Full compensation

Crossing of a major resonance can be avoided with the tune-spread compensation .

Evolution of r.m.s. Beam-size of the Antiproton Beam



a: no compensation

b: 50% compensation

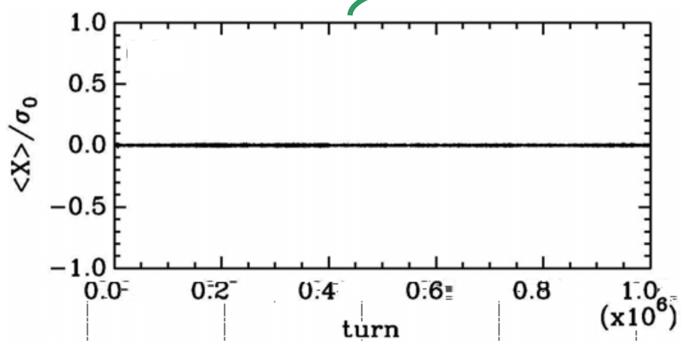
c: Full compensation

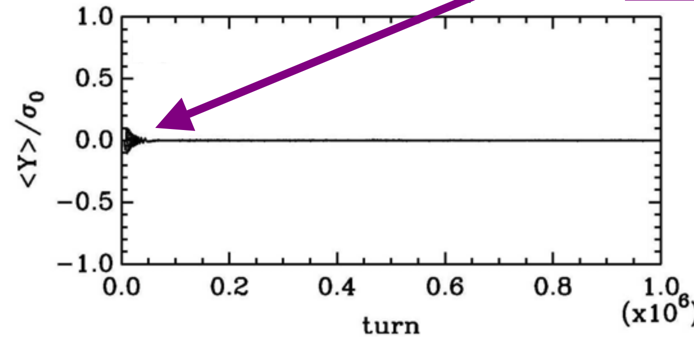
At a "bad" working point, a proper reduction of beam-beam tune spread could benefit beams.

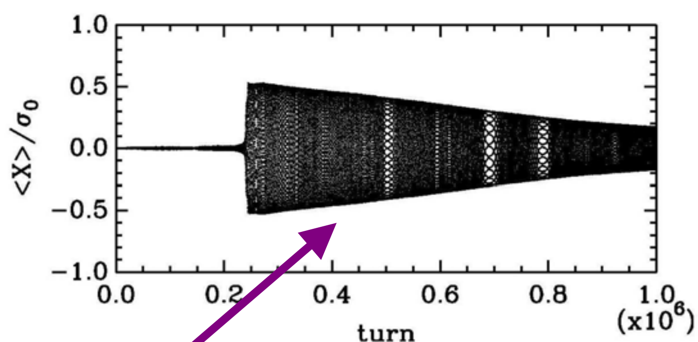
Beam-centroid Motion of the Antiproton Beam

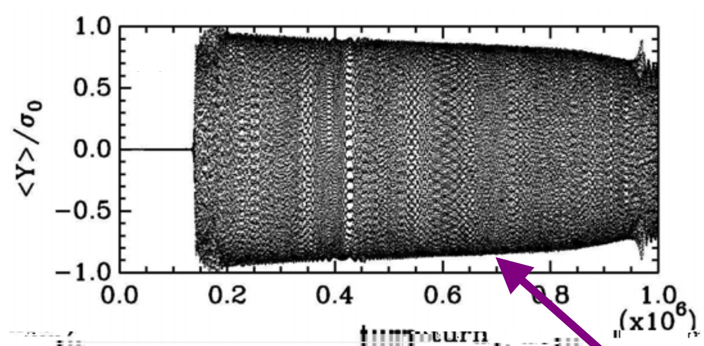
No compensation

Very strong Landau damping









50% compensation

Full compensation

Strong Landau damping

Weak Landau damping

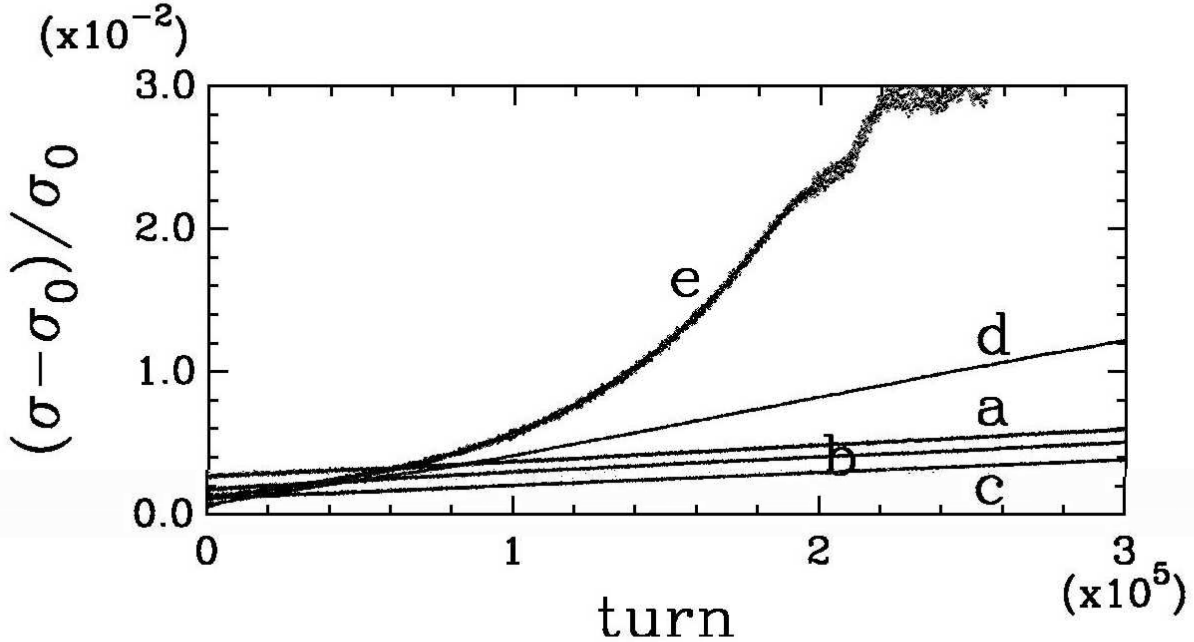
⇩

• A reduction of the beam-beam tune spread with electron beams could weaken the Landau damping that is important to the suppression of chaotic coherent beam-beam instability.

• At a “bad” working point, a reduction of the beam-beam tune spread could benefit beams if the weakened Landau damping is still enough to curb chaotic coherent beam-beam instability.

2π-Cancellation Between $\bar{p}$-p and $\bar{p}$-e Collision

Evolution of r.m.s. Beam-size of the Antiproton Beam



a: no compensation

b: 25% compensation

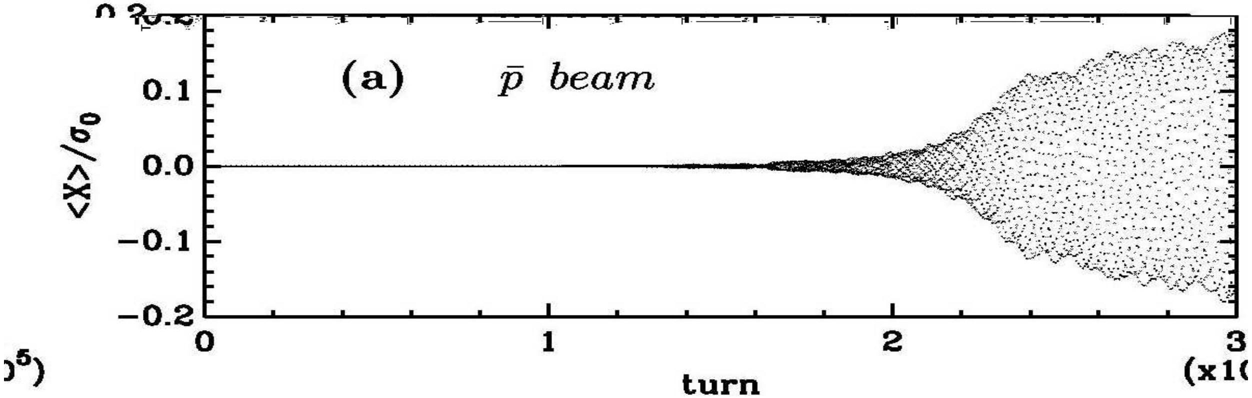
c: 50% compensation

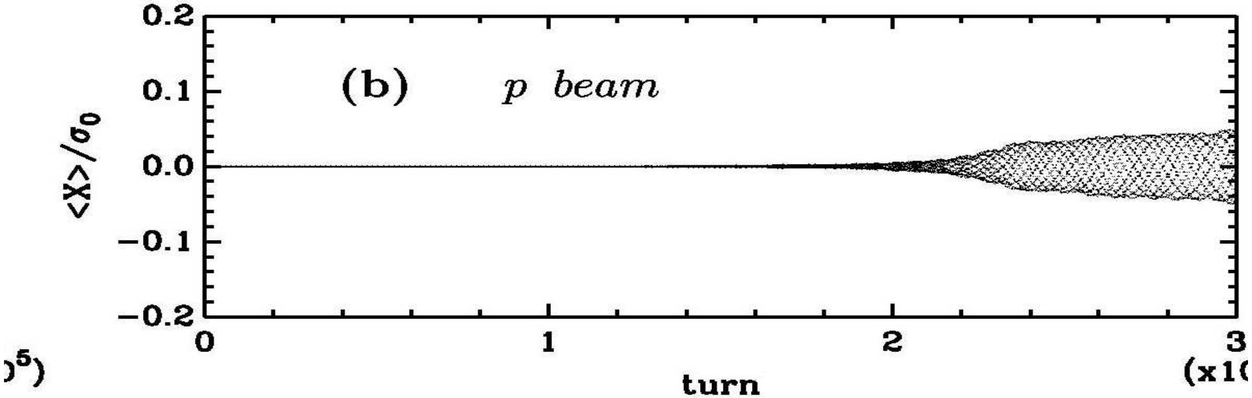
d: 75% compensation

e: Full compensation

Microscopic difference in the distribution of the e and p beam makes otherwise a perfect cancellation of beam-beam interactions failed in the full compensation due to the onset of the chaotic coherent beam-beam instability.

Chaotic Coherent Motion of the Antiproton beam with the full compensation





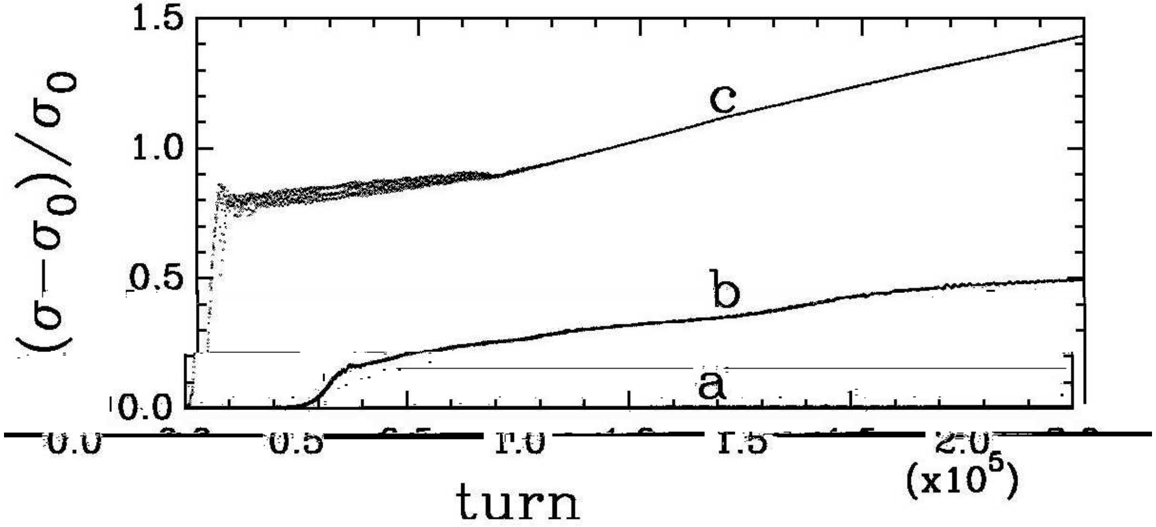
Compensation of Beam-Beam Tune Spread with Electron Beams

LHC MODEL

$(\nu_x, \nu_y) = (0.31, 0.32)$

$\xi_{pp} = 0.01$, 2IPs

Evolution of r.m.s. Beam-size of the proton Beam



a: no compensation

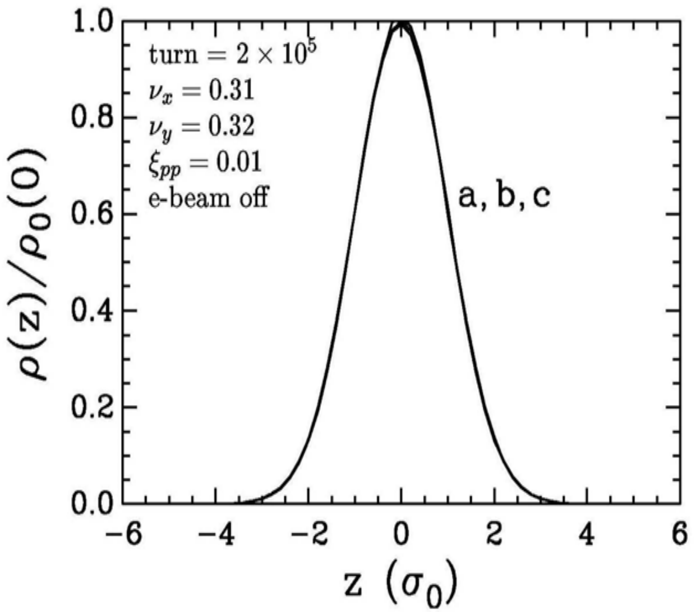
b: 50% compensation

c: Full compensation

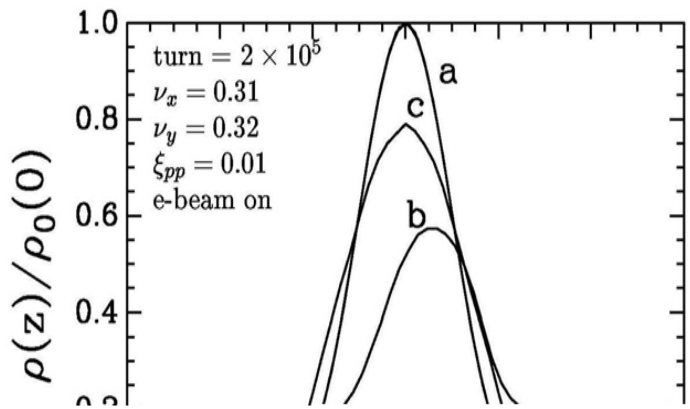
Similar to Tevatron, at a “good”working point, the compensation of beam-beam tune spread could damage the beam stability.

Effects of the Tune-Spread Compensation on Beam Particle Distribution

No Compensation



Full Compensation



a. Initial Gaussian distribution

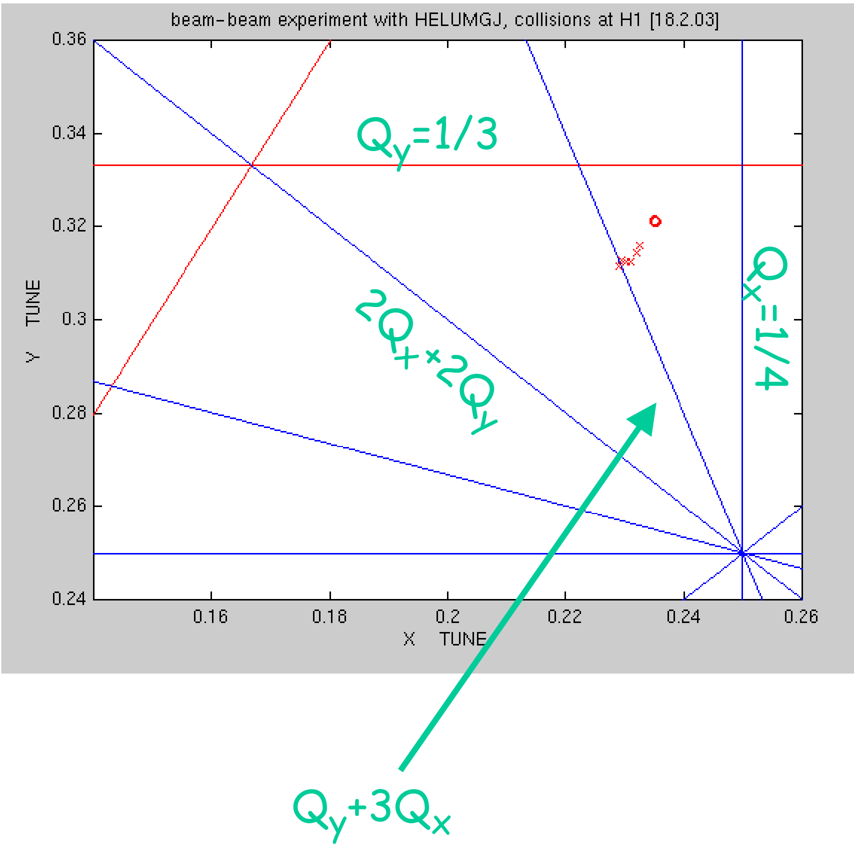
b. Projection in X

c. Projection in Y

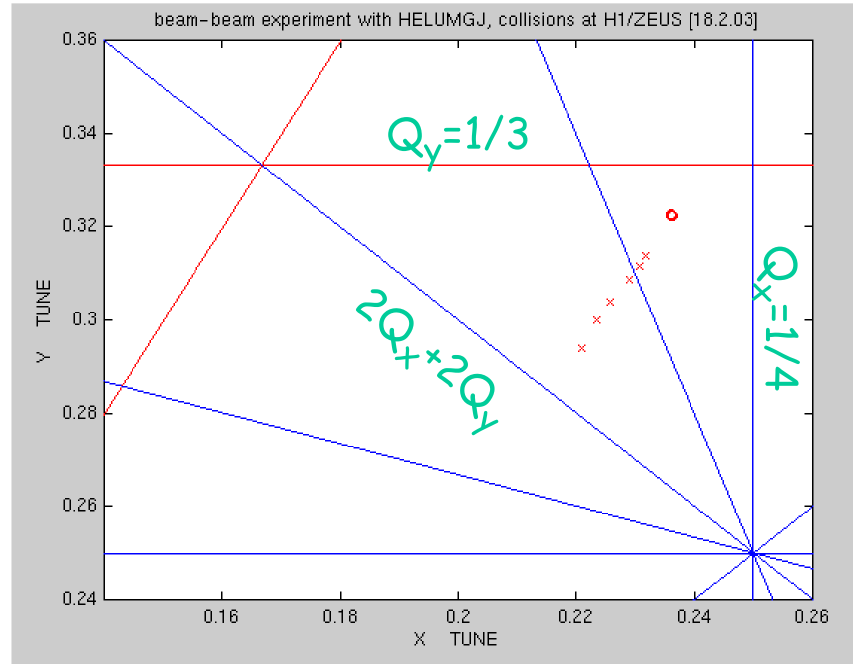
The compensation of beam-beam tune spread could damage beams by inducing the chaotic coherent beam-beam instability that leads to a formation of beam halos.

measured coherent tunes with collisions with 1 and 2 IPs (expmts IA/B)

IA) collisions at H1 only



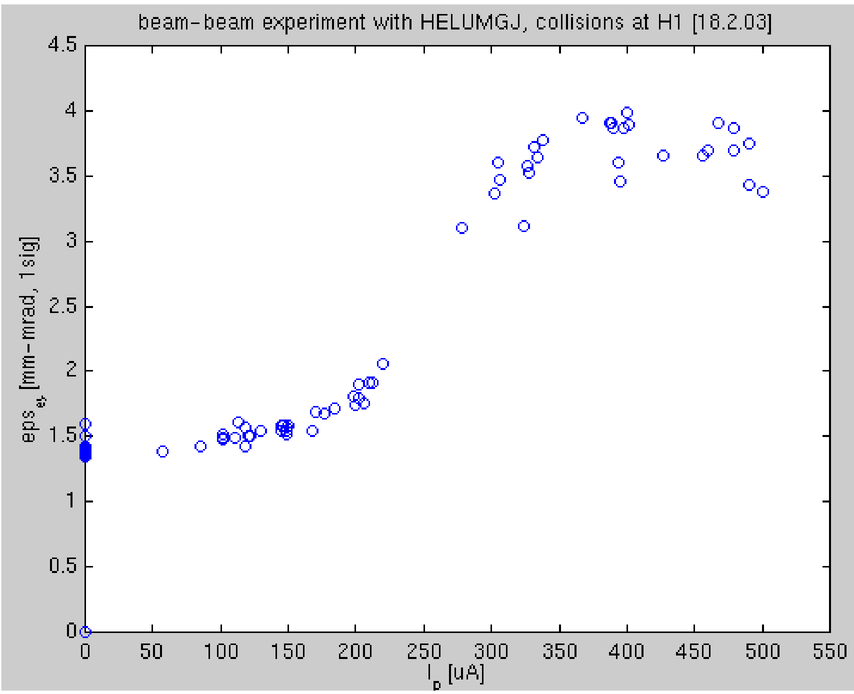
IB) collisions at H1 and ZEUS



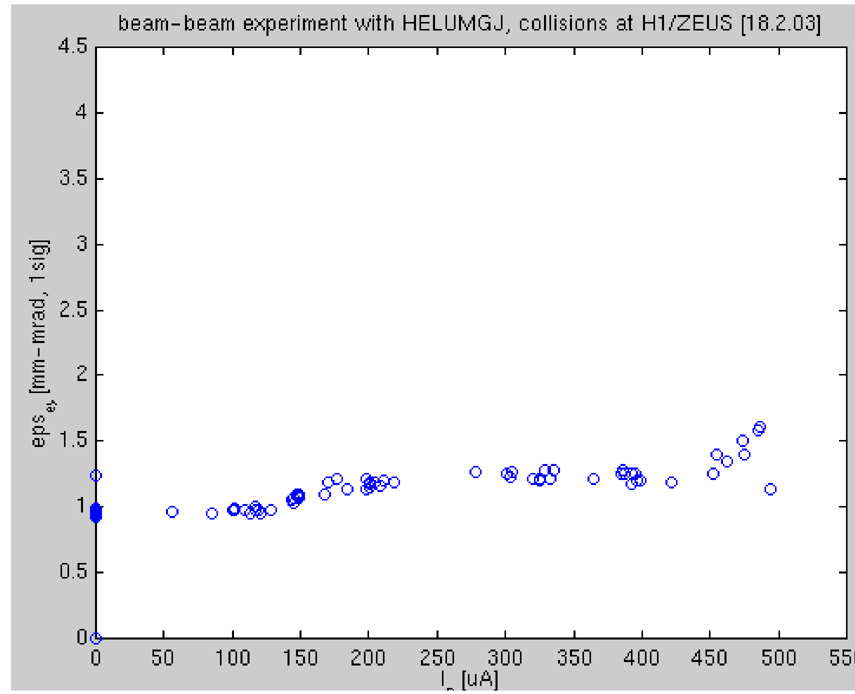
observation: with collisions only at H1, the beam appears to lock onto the Q_y + 3 Q_x resonance thereby causing the increased positron vertical emittance; why this is not the case with 2 IPs is unclear

measured positron y emittance vs proton beam current (expmts. IA/B)

IA) collisions at H1 only

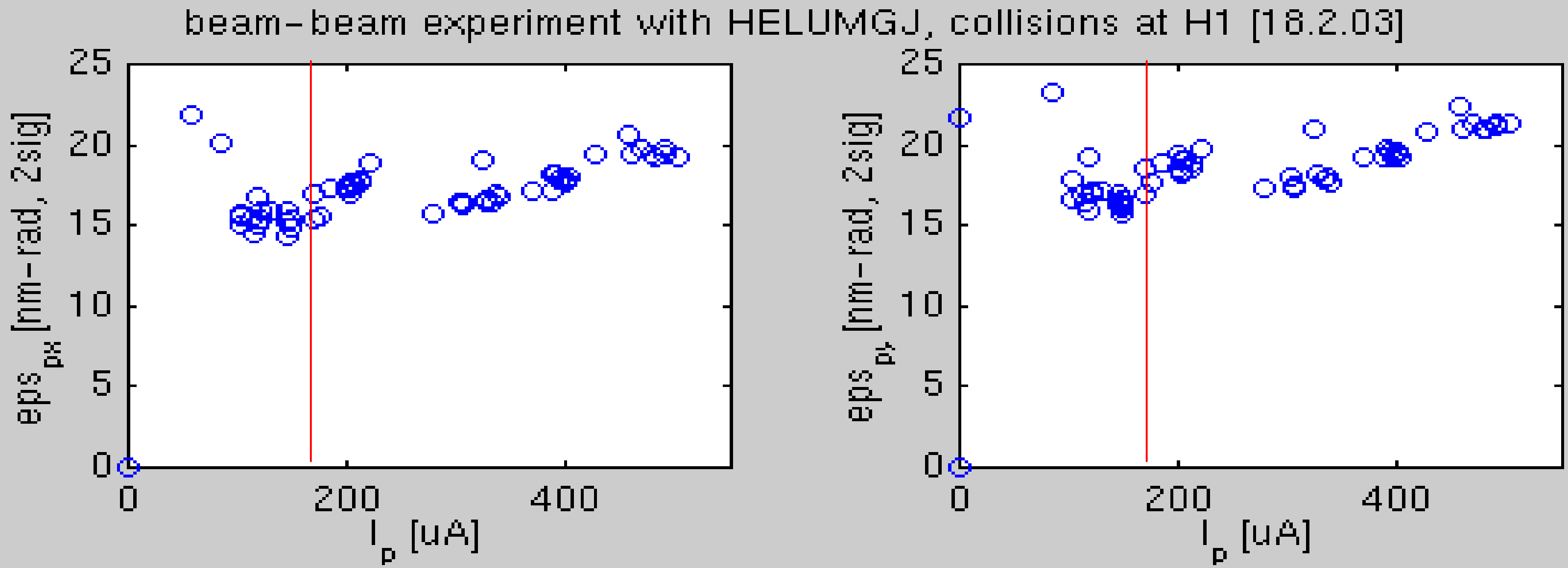


IB) collisions at H1 and ZEUS

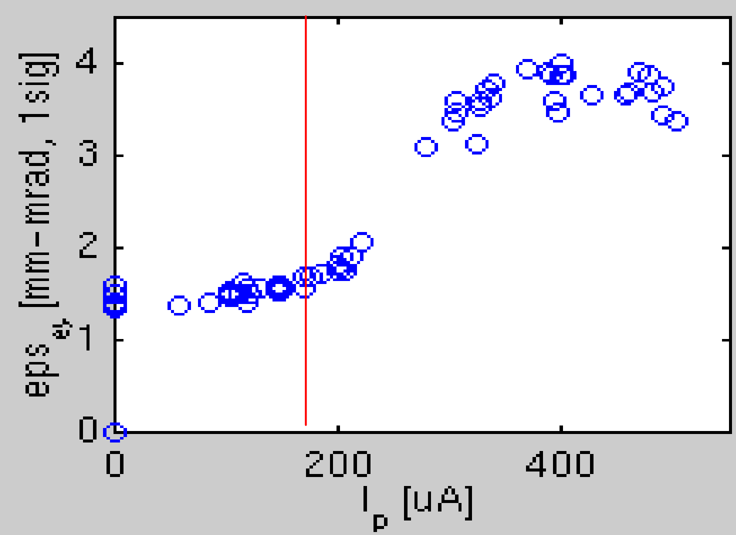


observation: significant increase in positron emittance with proton current in experiment with collisions at H1 only

$\varepsilon_{p,x}$, $\varepsilon_{p,y}$, $\varepsilon_{e,y}$ v.s. Proton Bunch Current



ξ_c : $I_p \approx 170\ \mu A$



Collective Beam-Beam Instability:

When $\xi_e > \xi_c$ the proton emittance increases with the beam-beam parameter of the positron beam. In this case, $\xi_e >> \xi_p$.

Summary

評 In a hadron collider with high-intensity beams, the beam-beam interaction is likely to be in the nonlinear regime in which the chaotic coherent beam-beam instability is important. In this situation, having a larger tune spread could be better to the beam stability since it could result in a stronger Landau damping that could suppress the coherent beam-beam instability and, moreover, the existence of a large tune spread reduces the possibility of trapping particles inside a bad resonance.

評 In the case that the working point is close to major resonance, a compensation of the beam-beam tunes spread up to certain degree could improve beam dynamics if the Landau damping is still strong enough for the suppression of the coherent beam-beam instability after the compensation or the damage effects of the nonlinear phase-dependent beam-beam perturbations can be outweighed by the benefit of the tune-spread compensation.